Strange hadron production at SIS energies: an update from HADES

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Strange hadron production at SIS energies: an update from HADES

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Abstract. We present and discuss recent experimental activities of the HADES collaboration on open and hidden strangeness production close or below the elementary NN threshold. Special emphasis is put on the feed-down from ϕ mesons to antikaons, the presence of the Ξ^- excess in cold nuclear matter and the comparison of statistical model rates to elementary p+p data. The implications for the interpretation of heavy-ion data are discussed as well.

1. Introduction

In the last two decades strange hadrons have been considered to represent particularly suitable probes of the high density phase of nuclear matter produced in relativistic heavy-ion collisions. For example, the relation of subthreshold-produced K^+ in light and heavy systems has been connected to the nuclear equation of state (EOS) at up to three times nuclear saturation [1, 2, 3], while phase space distributions and flow patterns are considered to be sensitive to the in-medium kaon-nucleon potential [4, 5, 6, 7].

Various aspects of strangeness production at energies available the Schwerionen Synchrotron (SIS) at GSI Darmstadt (up to kinetic beam energies of 2 A GeV) have been investigated by the FOPI and KaoS experiments and lately also by HADES (for reviews see [8, 9]). In contrast to strange particle production in elementary NN collisions, in heavy ion reactions multi-step processes as well as strangeness-exchange reactions like $\pi\Lambda \rightarrow NK^-$ are possible. Hence for any detailed understanding of strangeness production one has also to understand strangeness dynamics in the hot and dense medium. It is therefore important to measure as many particles with open or hidden strangeness as possible. Only recently data from FOPI [10] and HADES [11] has come close to fulfilling this requirement, and several still puzzling aspects have been revealed, e.g.:

- The strength of the kaon-nucleon potential, as derived from the comparison of data to models, yields values varying by about 50% for different data samples [12, 13, 14].
- The discovery of neutron stars with masses larger than 1.5 solar masses [15, 16] challenges the previously extracted constraints on the softness of the EOS [17].
- The large ϕ/K^- ratio reported in [18, 19] and the resulting feed-down which affects significantly the slope of the K^- questions the common interpretation of a later freeze-out of the K^- compared to K^+ [20]. In addition, new mechanisms seem to be required to reproduce microscopically the enhanced ϕ production [21, 22].
- Although transport codes do not reach chemical equilibrium within the lifetime of such collisions [9], the yields of produced hadrons can be well described within the framework of statistical models [11, 23], except for the Ξ^- (see below).
- The deep-subthreshold production of the Ξ^- which exceeds thermal model predictions by an order of magnitude [24, 25], can up to now, only be reproduced by one model [26].

In this paper we will review and investigate the status of the last three aspects.

2. Antikaons: slopes, yields and freeze-out

Systematic investigations of the KaoS collaboration in the nineties revealed a similar rise of kaon and antikaon yields with increasing centrality of the collision. In addition, the inverse slope parameters of the antikaons obtained from transverse spectra are systematically lower

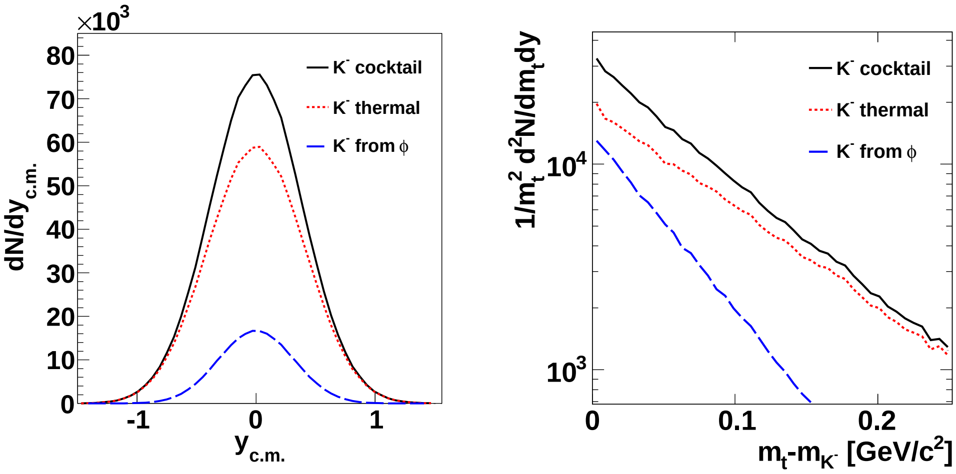

Figure 1. Left panel: Normalized rapidity density distributions of the thermal K^- and the ones resulting of a ϕ according to the measured yields in [19] . The black solid line shows the sum of the two distributions. Right panel: Simulated transverse mass spectra for K^- coming from a thermal source with a temperature of 89 MeV and those which stem from a ϕ decay. The resulting cocktail spectrum is shown as a black solid line.

than those observed for the kaons [8]. These findings have been interpreted with the help of transport models and the following conclusion has been drawn: the production of kaons and antikaons is coupled via strangeness exchange reactions, e.g. $\pi^- + \Lambda \to p + K^-$. As a consequence, the antikaons experience a later freeze-out than the kaons and hence have steeper transverse spectra. Furthermore people concluded that strangeness production close or below the elementary nucleon-nucleon (NN) threshold is very different to the one in elementary reactions [9]. The antikaon abundance has also been connected to the reduction of the effective antikaon mass via the strength of the strangeness exchange channels with an antikaon in the final state in [27].
Newer data from FOPI and HADES showed that for energies around $\sqrt{s_{NN}}$= 2.6 GeV the fraction of antikaons originating from a decay of the ϕ meson is about 20% and is hence not negligible [18, 19]. The resulting effect of the ϕ meson feed-down on the antikaon slopes has first been investigated in our previous work [20]. Simulating a cocktail of thermal and antikaons resulting from ϕ meson feed-down, according to the measured contributions in the Ar+KCl system, we found that within errors the inverse slope of the resulting K^- spectra agrees with the experimentally observed one, see Fig. 1. Hence the different slopes of the kaon and antikaon spectra do not necessarily call for a sequential freeze-out of the two kaon species but can be explained solely by ϕ feed-down. Meanwhile this issue has been investigated in greater detail by the FOPI collaboration [28].
Preliminary HADES Au+Au data taken at $\sqrt{s_{NN}}$= 2.4 GeV, where the complete set of particles carrying open and hidden strangeness is produced below the free nucleon-nucleon threshold, indicate a strong rise of the ϕ/K^- ratio towards lower energies [29], as predicted in a statistical model calculation [19]. For minimization of systematic errors due to efficiency corrections and extrapolations in rapidity, ratios of the corrected yields at mid-rapidity are used in this analysis. The resulting K^-/K^+ ratio can be directly compared to the previously obtained systematics at similar energy. The measured ratio K^-/K^+ fits into the trend observed at higher energies and extrapolated down to the beam energy of 1.23 A GeV, see left side of Fig.2: The ϕ/K^-

ratio is displayed on the right side of Fig.2; it shows a flat trend at high energies, and a rise towards lower energies. This rise can be reproduced in the framework of a statistical model, if the suppression of strangeness is handled by introducing a strangeness correlation radius R_c within which strangeness has to be exactly conserved [30]. In this context it is important to realize that, as the ϕ conserves strangeness by definition, it is not suppressed by the strangeness correlation parameter in contrast to the other particles containing strange quarks.
Recently, feed down from higher lying baryonic resonances have been included in UrQMD in order to be able to describe the energy dependence of the ϕ/K^- ratio also in a transport code [31]. The authors tuned the mass depending branching ratio of high lying baryon resonances, namely the $N^*(1990)$, $N^*(2080)$, $N^*(2190)$, $N^*(2220)$ and $N^*(2250)$, in a transport code to match elementary data on ϕ meson production. As a result, the ϕ/K^- in Ar+KCl is successfully reproduced, as well as the shape of the excitation function. At higher energies the model undershoots the data and the preliminary Au+Au data point is also not fully reproduced.
It will be very interesting, as soon as the final data becomes available, to compare besides the pure yields, the shape of the transverse particle spectra, as they are strongly dependent on the contribution from resonances as investigated in [32] for kaons with respect to the sensitivity of the spectral shape to the kaon nucleon potential.

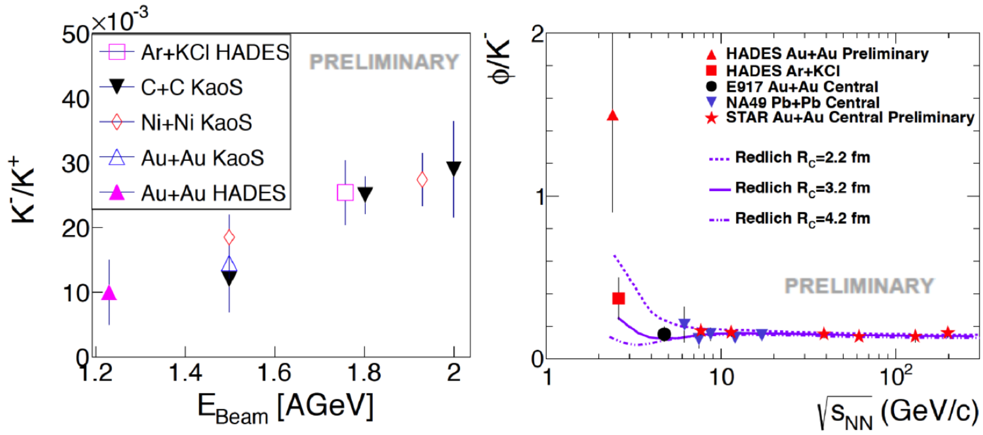

Figure 2. Left: Kinetic beam energy excitation function of the K^-/K^+ ratio for various colliding systems. Data is taken from [8, 19]. The preliminary ratio at midrapidity extracted in this work, fits nicely to the trend. Right: The ϕ/K^- ratio shows a flat trend at high energies and a sharp rise towards lower energies, which can be explained within the statistical model framework using a proper strangeness correlation radius R_c. The data is taken from [19].

3. Statistical equilibrium rates

In the last 30 years statistical hadronization models have been established as a successful tool to fit particle yields or yield ratios from relativistic and ultrarelativistic heavy-ion collisions [33, 34, 35] with only a few parameters. The extracted freeze-out parameters show a striking regularity, lining up on a curve in the temperature-baryochemical potential plane, connecting smoothly data from the GeV to the TeV regime [36] . These findings have been widely interpreted as a hint that (local) chemical equilibrium is achieved in such collisions.
Since the days of Hagedorn [37], statistical methods have also been used to predict particle production in elementary reactions. Recently two groups applied the same model, which successfully describes hadron yields in heavy-ion collisions, also for elementary reactions but reached very different conclusions. While the authors of [38, 39] found good agreement for yields and even transverse momentum spectra obtained in elementary $e^+ + e^-$, the authors of [40] found significantly worse agreement between model and experimental yields.

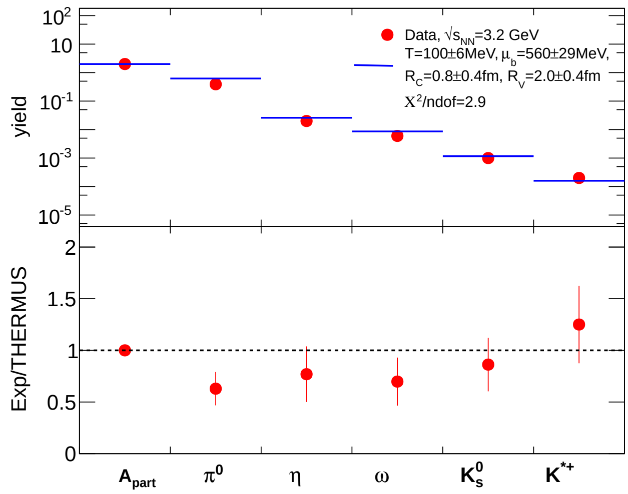

Figure 3. The upper plot shows the yields of secondary hadrons in p+p reactions (filled red circles) and the corresponding THERMUS fit values (blue bars) as well as the obtained fit parameters. The lower plot shows the ratio of the experimental value and the statistical model value.

In order to investigate this issue, we use the yields of hadrons produced in elementary p+p collisions at $\sqrt{s_{NN}}$= 3.2 GeV measured with HADES, which have recently become available [41, 42, 43]. We apply a similar fit as in our previous work [11] but use an updated version of THERMUS (v3.0) [44]. We use the mixed canonical ensemble where strangeness is exactly conserved while all other quantum numbers are calculated grand canonically and constrain the charge chemical potential μ_Q using the ratio of the baryon and charge numbers of the collision system.

We state that the yield of the ϕ meson is of particular interest, because of its different sensitivity to the strangeness suppression parameters γ_s and R_c. As the ϕ conserves strangeness by definition as a $s\bar{s}$ state its yield is not suppressed in the R_c formalism, while strongly suppressed when γ_s is used. We found in [11] that the ϕ yield is well described using R_c and therefore stick to this way of suppressing strange particle yields in our statistical model calculations.

We simultaneously fit the yields of the neutral pions, the η, the ω and the kaons, as well as the mean number of participants $\langle A_{part}\rangle$ and constrain the charge chemical potential μ_Q by the initial charge to baryon ratio. We find the following values for chemical freeze-out parameters: T_{chem} = (100 ± 6) MeV, μ_b = (560 ± 29) MeV, the strangeness correlation radius results as $R_c = (0.8 \pm 0.4)$ fm and the radius of the whole fireball $R = (2.0 \pm 0.4)$ fm with χ^2/d.o.f.=2.9. A detailed comparison of the data with our the statistical model fit is shown in the upper part of Fig. 3, while the lower part of this figure depicts the ratio of data. The overall agreement between model and data is comparable to the outcome of our previous work where we fitted hadron yields obtained from Ar+KCl collisions at $\sqrt{s_{NN}}$= 2.6 GeV. This is rather surprising as one naively expects a larger amount of thermalization in the larger Ar+KCl system and hence less deviation from statistical equilibrium values. Furthermore, the p+p freeze-out point fits quite well to the previously observed regularity of freeze-out points in the $T - \mu_b$ plane, displayed in Fig. 4, where the extracted point of this work are displayed together with similar points extracted in [45] and [36].

This brings us back to the introduction; while the success of the statistical model in describing particle rates from heavy-ion collision is often implicitly connected to a thermalization of the created system, the success of the model in describing the p+p data at $\sqrt{s_{NN}}$= 3.2 GeV strongly questions this connection.

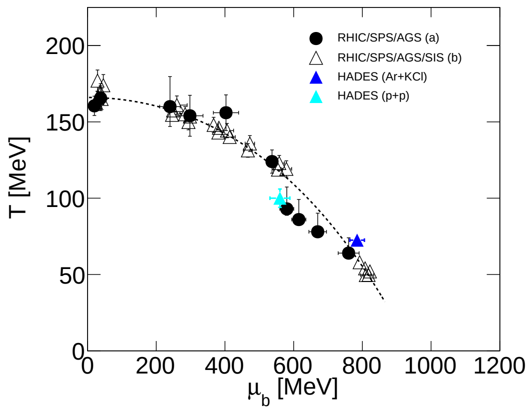

Figure 4. Freeze-out points in the $T - \mu_b$ plane obtained from statistical model fits to hadron yields or yield ratios [45] (filled symbols) and [36] (open symbols). In addition, the HADES points for Ar+KCl [11] (blue triangle) and the p+p point (cyan triangle) from this work are displayed. The dotted line corresponds to a common freeze-out condition of 1 GeV fixed energy per baryon.

4. The Ξ^- excess

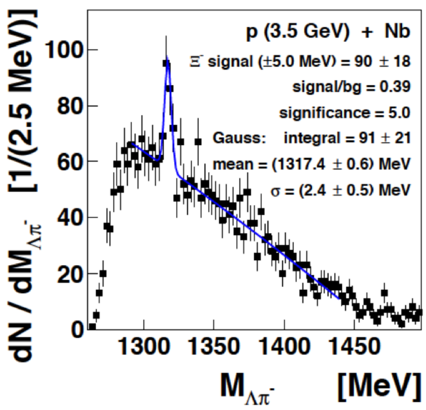

Figure 5. Invariant mass spectrum of Λ hyperons and negative pions obtained in p+Nb collisions at $\sqrt{s_{NN}}$= 3.2 GeV. A clear peak corresponding to the Ξ^- signal is visible.

Recent data of HADES revealed that the excess of the Ξ^- over several state of the art models shows up also in p+Nb reactions at $\sqrt{s_{NN}}$= 3.2 GeV [46]. The extracted experimental signal in the invariant mass spectrum is displayed in Fig. 5. In addition, the energy excitation function of the Ξ^- Lambda ratio for various colliding systems is displayed in Fig. 6. While the open symbols correspond to heavy-ion data, the filled symbols represent proton induced collisions on nuclei. The black line corresponds to a simple parameterization fitted to the proton induced data of the form

$$F(\sqrt{s_{NN}}) = C \times \left(1 - \left[\frac{D}{\sqrt{s_{NN}}}\right]^G\right)^H . \quad (1)$$

The inlay shows a zoom to the area of the HADES p+Nb data point and the comparison to three different models. The upper star symbol corresponds to the yield obtained from a THERMUS (v2.3) fit to p+Nb data similar to the one discussed in this work. While the lower star symbol corresponds to the yield obtained via the UrQMD (v3.4) transport code, the intermediate point results from a GiBUU transport calculation.
The presence of the Ξ^- excess in cold nuclear matter has several interesting implications for the interpretation of the heavy-ion data as its origin seems to be already in the elementary channels without the involvement of many body effects in the medium [26, 47]. Therefore, the increased cross sections of strangeness exchange reactions, which were found to be sufficient to explain the high yield in, seem to be questionable as they are highly unlikely to play an important role in

p+Nb reactions. Also, the invoked [23] catalytic strangeness production by secondary processes like $\pi + Y \rightarrow \Xi + K$ are strongly suppressed in cold nuclear matter.

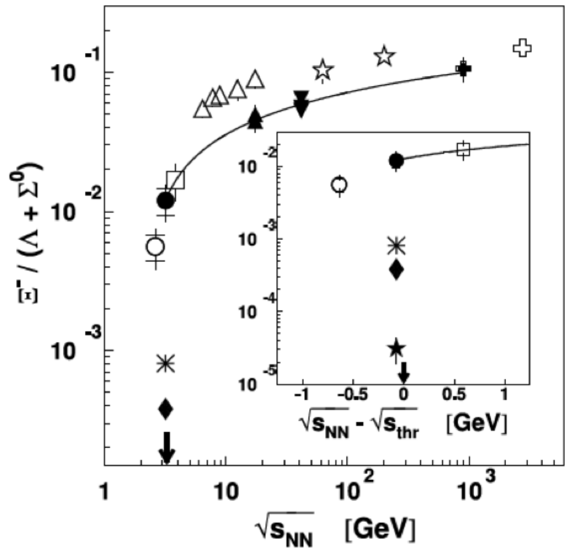

Figure 6. Excitation function of the Ξ^-/Λ ratio for various colliding systems. The open symbols correspond to heavy-ion data, the filled symbols represent data from p+A collisions. The black line corresponds to a simple parameterization fitted to the p+A data, see text for details. The inlay shows a zoom to the area of the HADES p+Nb data point and the comparison to three different models. The upper star symbol corresponds to a the yield obtained from a THERMUS (v2.3) fit to p+Nb data. The lower star symbol corresponds to the yield obtained via the UrQMD (v3.4) transport code and the intermediate point a GiBUU transport calculation.

Recently the same mechanism of feed-down of the high invariant mass tails of baryonic resonances used to explain the ϕ meson yield by the UrQMD group was also used for the Ξ^- hyperon. Due to the lack of elementary data the model is tuned to match our p+Nb data [32]. After this tuning it is not too surprising that the model is able to describe the excess observed in Ar+KCl without further tuning.
The technique of mass dependent branching ratios for broad resonances has been successfully applied in order to describe the dilepton spectra at low energies as pointed out in several publications [48, 49]. Note, how even that tuned branching ratios are still consistent with the OZI rule there is yet no experimental evidence for the decay of the N^* resonance to final states containing a ϕ meson or a Ξ hyperon.

5. Summary

We showed that for all three topics discussed here elementary and cold nuclear matter data are needed for the interpretation of heavy-ion data. In particular:

- The observed large ϕ/K^- ratio and the resulting feed-down lowers significantly the slope of the K^-. Hence a later freeze-out of antikaons compared to kaons is not necessarily needed to explain the different slopes of both kaon species. Furthermore, the rise towards lower energies can also be reproduced, at least to some extent, in transport codes after tuning of the ϕ cross sections on elementary data.
- We find that a statistical model fit to elementary p+p data is able to describe the yields with the same parameters as used for Ar+KCl with comparable accuracy and this questions the often implicitly used connection to a thermalized system.
- The presence of the Ξ^- excess also in cold nuclear matter rules out more exotic explanations involving multistep processes in heavy-ion collisions. Feed-down from high mass tails of baryonic resonances remains a possible explanation but at the moment it is not very well constrained by both the experimental data and the theoretical treatment.

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[1] C. Sturm *et al.* [KaoS Collaboration], Phys. Rev. Lett. **86**, 39 (2001).
[2] C. Fuchs, A. Faessler, E. Zabrodin, Phys. Rev. Lett. **86**, 1974 (2001).
[3] C. Hartnack, H. Oeschler, J. Aichelin, Phys. Rev. Lett. **96**, 012302 (2006).
[4] J. Schaffner-Bielich, J. Bondorf, A. Mishustin, Nucl. Phys. A **625**, 325 (1997).
[5] W. Cassing, E. L. Bratkovskaya, U. Mosel, S. Teis, A. Sibirtsev, Nucl . Phys. A **614** 415 (1997).
[6] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **110** 142301 (2013).
[7] V. Zinyuk *et al.* [FOPI Collaboration], arXiv:1403.1504 [nucl-ex].
[8] A. Forster, F. Uhlig, I. Bottcher, D. Brill, M. Debowski *et al.*, Phys. Rev. C **75** 024906 (2007).
[9] C. Hartnack, H. Oeschler, Y. Leifels, E. L. Bratkovskaya, J. Aichelin, Phys. Rept. **510** 119 (2012).
[10] N. Bastid *et al.* [FOPI Collaboration], Phys. Rev. C **76** 024906 (2007).
[11] G. Agakishiev *et al.* [HADES Collaboration], Eur. Phys. J. A **47** 21 (2011).
[12] M. L. Benabderrahmane *et al.* [FOPI Collaboration], Phys. Rev. Lett. **102** 182501 (2009).
[13] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **82** 044907 (2010).
[14] G. Agakishiev *et al.* [HADES Collaboration], arXiv:1404.7011 [nucl-ex].
[15] P. Demorest *et al.*, Nature **476**, 1081 (2010).
[16] J. Antoniadis *et al.*, Science **340**, 6131 (2013).
[17] A. W. Thomas *et al.*, EPJ Web of Conferences **63**, 03004 (2013).
[18] A. Mangiarotti *et al.* [FOPI Collaboration], Nucl. Phys. A **714** 89 (2003).
[19] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **80** 025209 (2009).
[20] M. Lorenz *et al.* [HADES Collaboration], PoS BORMIO **2010** 038 (2010).
[21] B. Tomasik and E. E. Kolomeitsev, Acta Phys. Polon. Supp. **5** 201 (2012).
[22] B. Kampfer, R. Kotte, C. Hartnack, J. Aichelin, J. Phys. G **28** 2035 (2002).
[23] E. E. Kolomeitsev, B. Tomasik, D. N. Voskresensky, Phys. Rev. C **86** 054909 (2012).
[24] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. Lett. **103** 132301 (2009).
[25] J. Steinheimer, T. Lang, H. van Hees, A. S. Botvina et al., J. Phys. Conf. Ser. **509** 012002 (2014).
[26] F. Li, L. -W. Chen, C. M. Ko and S. H. Lee, Phys. Rev. C **85** 064902 (2012).
[27] W. Cassing, E. L. Bratkovskaya, U. Mosel, S. Teis, A. Sibirtsev, Nucl. Phys. A **614** (1997) 415.
[28] K. Piasecki *et al.* [FOPI Collaboration], Phys. Rev. C **91** 5, 054904, (2015).
[29] M. Lorenz [HADES Collaboration], Nucl. Phys. A **931**, 785, (2014).
[30] J. Cleymans *et al.*, Phys. Rev. C 59, 1663 (1999).
[31] J. Steinheimer, M. Bleicher, arXiv:1503.07305 [nucl-th].
[32] J. Steinheimer, M. Bleicher, EPJ Web Conf. **97**, 00026 (2015).
[33] P. Braun-Munzinger, K. Redlich and J. Stachel, arXiv:nucl-th/0304013 (2003).
[34] A. N. Tawfik, Int. J. Mod. Phys. A **29** 17, 1430021 (2014).
[35] M. Floris, Nucl. Phys. A **931** 103 (2014).
[36] J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, Phys. Rev. C **73**, 034905 (2006).
[37] R. Hagedorn, Nuovo Cim. Suppl. **3** 147 (1965).
[38] F. Becattini, G. Passaleva, Eur. Phys. J. C **23** 551 (2002).
[39] F. Becattini, P. Castorina, J. Manninen, H. Satz, Eur. Phys. J. C **56** 493 (2008).
[40] A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B **675**, 312, (2009).
[41] G. Agakishiev *et al.* [HADES Collaboration], Eur. Phys. J. A **48**, 64, (2012).
[42] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **90**, 015202, (2014).
[43] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **92**, 024903, (2015).
[44] S. Wheaton, J. Cleymans, Comput. Phys. Commun. **180** 84 (2009).
[45] A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772**, 167 (2006).
[46] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. Lett. **114** 21, 212301, (2015).
[47] G. Graef, J. Steinheimer, F. Li, M. Bleicher, Phys. Rev. C **90**, 064909, (2014).
[48] E. L. Bratkovskaya, J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, Phys. Rev. C **87** 064907 (2013).
[49] J. Weil, H. van Hees, U. Mosel, Eur. Phys. J. A **48** 111 (2012).